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PROGRESS IN DIAGNOSTIC TECHNIQUES FOR SC CAVITIES

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Introduction

While routinely achieved performance characteristics of superconducting cavities have now reached a level which makes them useful in large scale applications, achieving this level has come only through the knowledge gained by systematic studies of performance limiting phenomena[1]. Despite the very real progress that has been made, the routine performance of superconducting cavities still falls far short of both the theoretical expectations and the performance of a few exceptional examples.

It is the task of systematically applied diagnostic techiques to reveal additional information concerning the response of superconducting surfaces to applied RF fields. Reviews of the essential tools of the trade have been presented in each of the two previous Workshops[2,3] and will not be discussed again here. We will direct our attention to discussions of recent developments in diagnostic techniques. Whereas an entire session of this Workshop is devoted to discussion of the study of the new high T_c materials, the diagnostic techniques unique to those studies will also be omitted here.

Thermometry in Superfluid Helium

One of the most commonly used diagnostic tools continues to be that of thermometry in a subcooled He bath[4]. A customary arrangement for cavities of cylindrical symmetry employs a set of sliding thermometers on a rotating frame. A careful analysis of this procedure and its application was given by Müller at the CERN Workshop in 1984.[3] The resulting temperature maps have yielded very useful information about field limiting defects and electron loading phenomena. This information has permitted the "guided repair" of cavities and the improvement of surface treatments and fabrication techniques. In the mean time very little progress has been made in the experimental investigation of residual loss mechanisms. Discussions of residual resistance usually only have Q measurements at low temperature as the data with which to work.[5] This, of course, forces one to make the assumption of uniform surface resistance throughout the cavity.

Efforts to examine the frequency dependence of residual resistance by measuring Q values of multiple modes in a single cavity have suggested that an inhomogeneous residual resistance is to be expected.[6] In addition, theoretical considerations predict residual loss mechanisms which are dependent both on surface electric and magnetic fields.[7] It is also possible that normal conducting defects, though stabilized against breakdown through the use of high thermal conductivity material, may contribute a dominant part of the residual losses in a cavity.[8] Some localized lossy regions of

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cavities have been identified with subcooled thermometry, but any residual loss mechanism which contributes less than the BCS surface resistance at 2.2 K will remain undetected by this method. This limits the observable R_{res} of niobium cavities to about 100 nOhm at a frequency of 3 GHz and about 30 nOhm at 1.5 GHz. It is thus necessary to lower the helium bath temperature below T_{λ} in order to examine cavities with Q-values greater than 10^{10} at frequencies above 1 GHz. In addition, because of the temperature dependence of R_{BCS}, there exists an upper limit to the surface magnetic field at which subcooled temperature mapping can be applied.[3] At this point global heating dominates the temperature response of the cavity wall. Since this limit (H_{peak} = 250 Oe at 3 GHz, H_{peak} = 500 Oe at 1.5 GHz) is now quite often exceeded in niobium cavities made of high thermal conductivity material, the need for surface temperature measurements in superfluid helium is inescapable.

Unlike the situation one has in subcooled thermometry, in a superfluid helium bath there does not exist a significantly thick layer of warmed up liquid helium just outside the cavity wall for the thermometer to sense. The extremely high thermal conductivity of superfluid helium places two requirements on sensors in order to be useful in measuring the increased surface temperature of a cavity:

1) good thermal contact to the metal surface
2) efficient thermal insulation against the surrounding superfluid helium bath.

G. Müller and P. Kneisel have developed two types of thermometers which satisfy the above requirements: "thick film" resistors directly painted onto the surface and removable, well-insulated temperature sensors.[9]

"Thick film" thermometers consist of consecutively deposited layers: an electrically isolating coating, a lead pattern, the temperature sensitive film, and, optionally, a thermally insulating layer. Various materials were tested for each layer. The thickness of the first layer was optimized to have at least 20 MOhm electrical insulation. Sensors were sized so as to provide a resistance on the order of 10 kOhms at 1.5 K.

The best results have been obtained reproducibly with painted "thick film" thermometers consisting of five layers[10]: Nb_2O_5, Delta Coate 151, silver paint, Electrodag 501, and Stycast 2850 FT (See Figure 1). These thermometers have a relative resistance change of $(\Delta R/R)/(\Delta T/T) = 1.8$ between 1.4 K and 2.0 K.

The construction of the removable, well-insulated type thermometer is illustrated in Figure 2. An Allen-Bradley 1/8 Watt, 100 Ohm carbon resistor is used as the temperature sensitive element because these offer a high relative resistance change of 4.5 to 3. Efficient thermal insulation is provided by a STYCAST 2850 FT housing and Apiezon N grease is used as a thermal bonding agent between the copper housing of the temperature sensor and the niobium surface. A spring contact probe ("pogo stick") is glued into the housing and provides reproducible pressure and placement of the thermometer.

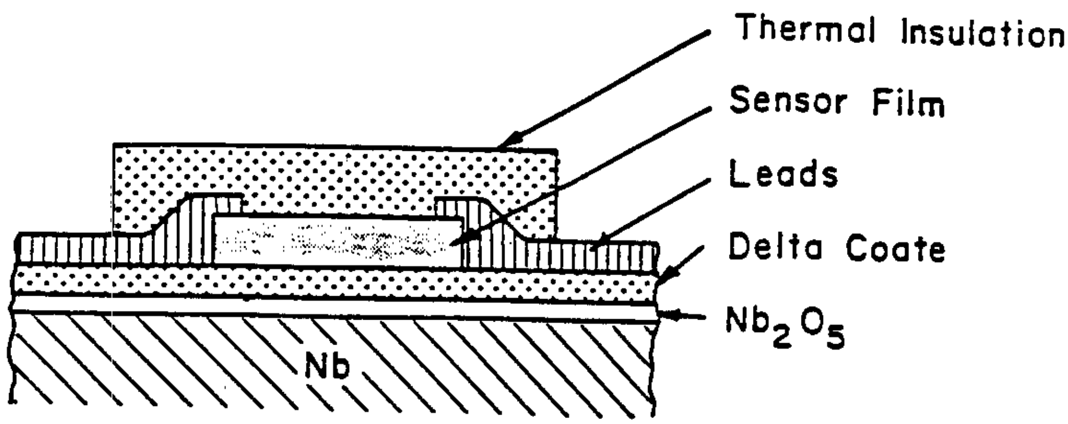

Figure 1: Schematic cross section of a "thick film" thermometer.

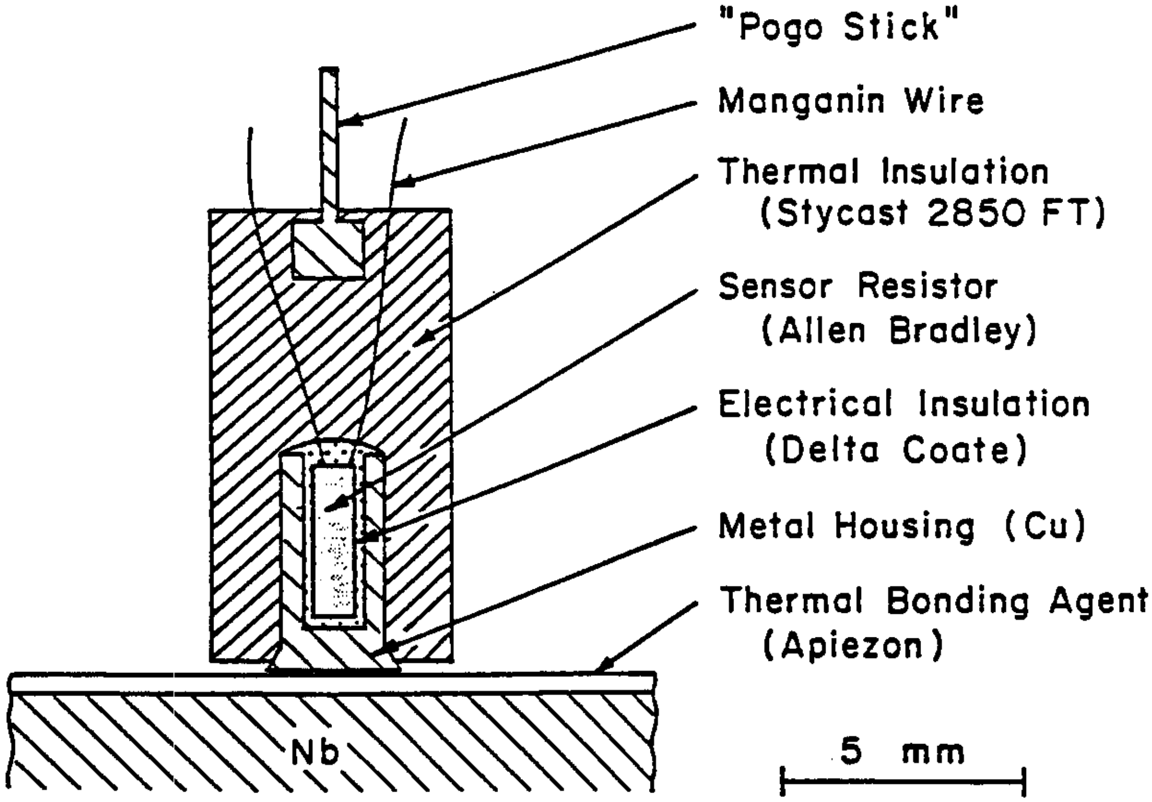

Figure 2: Schematic cross section of a removable temperature probe.

Calibration of both types of sensors show the expected linear dependence of the temperature signal on the heat flux density over several orders of magnitude up to saturation levels, and can be used over the whole interesting bath temperature range of 1.4 K to 2.0 K. Relative to model calculations, ΔT measurement efficiencies of up to 60% have been achieved reproducibly with the removable thermometer design and efficiencies up to 150% of the calculated temperature signal have been achieved with the "thick film" thermometers painted on niobium surfaces. Figure 3 shows the response of a removable thermometer at 1.43 K to a known point like heat source through 1/16" reactor grade niobium.

Employed as a diagnostic technique for the study of loss mechanisms in superconducting RF cavities, thermometry in a superfluid helium bath has the advantage of providing improved spatial resolution of the heat distributions. (See Figure 4). For point like losses in a cavity one may expect a full width at half maximum temperature signal of 4-8 mm for $^1/_{16}$" niobium, depending on the thermal conductivity and the Kapitza resistance of the material.

The first application of the removable thermometers to measurements on an RF cavity in a superfluid helium bath involved a frame of 100 sensors mounted on the endplate of a TE_{011} cavity.[11] The cylindrical cavity, built out of reactor grade niobium, has a demountable endplate as shown in Figure 5. The dimensions have been chosen such that the maximum magnetic field on the cavity surface appears on the endplate. The cavity resonates at 3.5 GHz in the TE_{011} mode, and during measurements the coupling is from below. The demountable endplate is sized to fit into existing SEM's in order to permit future surface studies. The thermometers are arranged in concentric circles coinciding with the magnetic field contours.

The resistance changes of the sensors are measured by an AC bridge circuit with a lock-in amplifier as the phase sensitive detector. This technique offers a resolution of $\Delta R/R = 3{*}10^{-6}$ for an integration time of 100 msec, corresponding to a temperature sensitivity of $\Delta T \approx 1 \mu K$.

While the thermometer characterization studies were carried out manually, an automated system has been developed in order to reduce the scan time for 100 thermometers. (See Figure 6). Depending on the resistance resolution selected, 20-50 minutes are required for a scan through all 100 sensors. Figure 7 is an example of a temperature map from the TE_{011} cavity endplate. One limitation of the present arrangement is that the thermometer spacing is limited to about 10 mm, while the FWHM ~ 5 mm for the heat signal from a point like source on the cavity surface.

Three kinds of losses have been identified from the maps taken to date:

1) losses at the outer rim of the endplate caused by poor RF contact between the removable endplate and the cavity body,
2) localized regions of enhanced losses, and
3) wider areas of background losses causing much lower temperature signals.

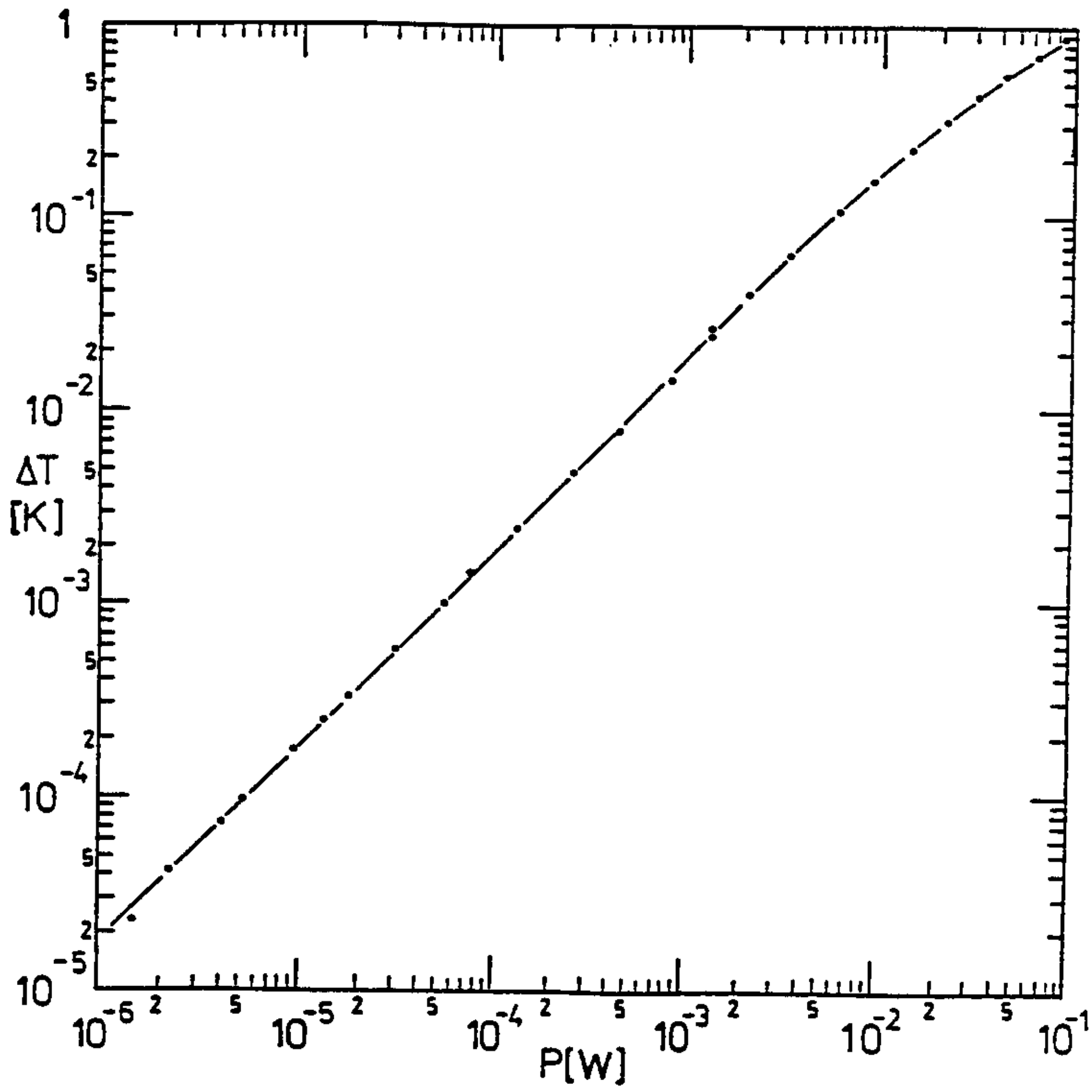

Figure 3: Calibration curve ΔT vs. heater power, P, for the removable temperature probes in superfluid helium at 1.43 K.

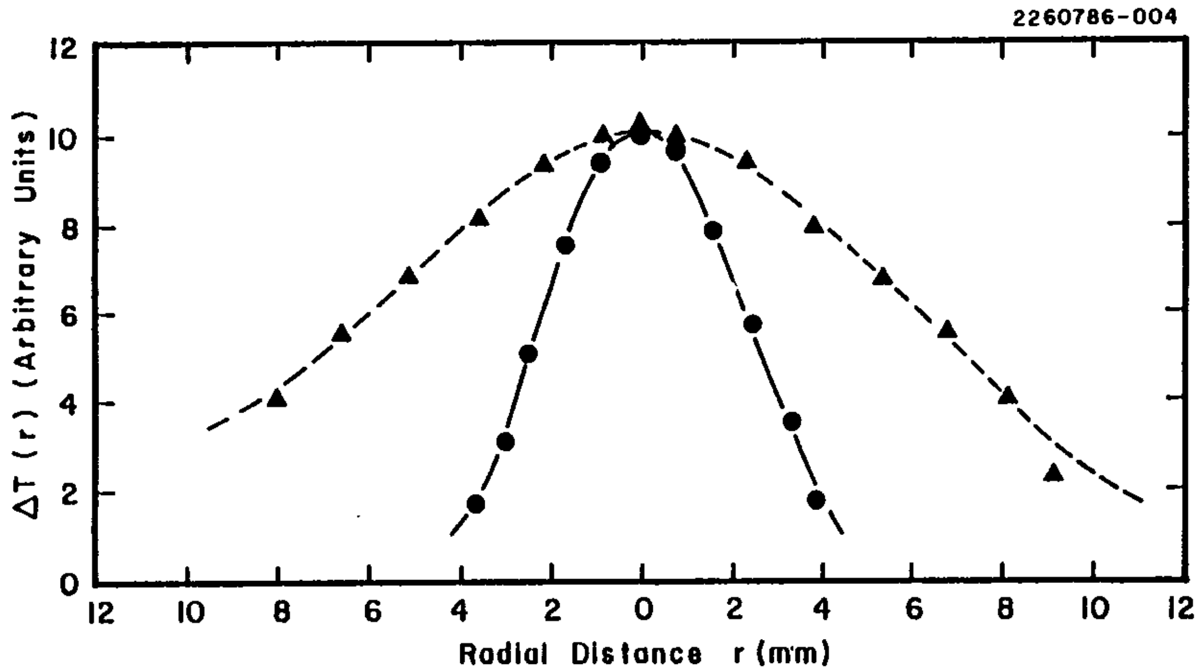

Figure 4: Spatial distribution of the temperature signal ΔT measured in a) subcooled helium at 2.2 K and b) superfluid helium at 1.5 K.

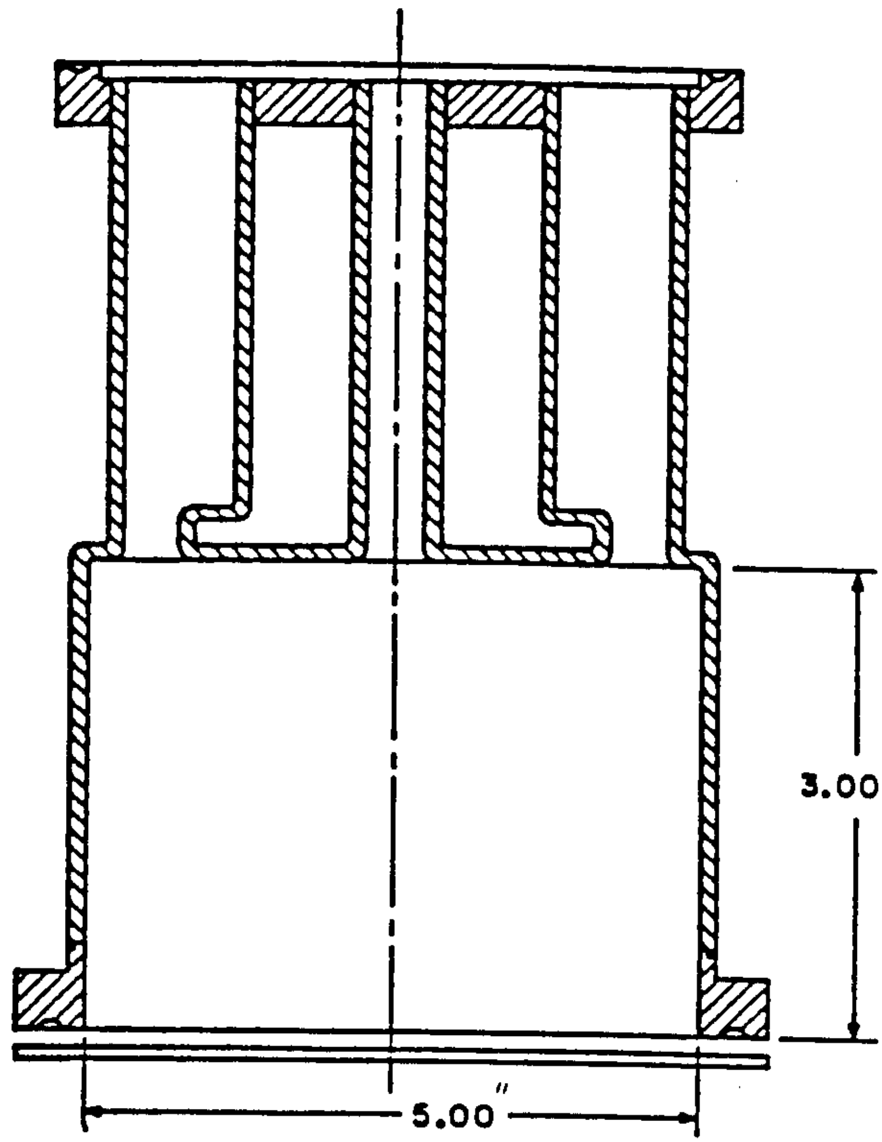

Figure 5: Cross section of TE_{011} cavity.

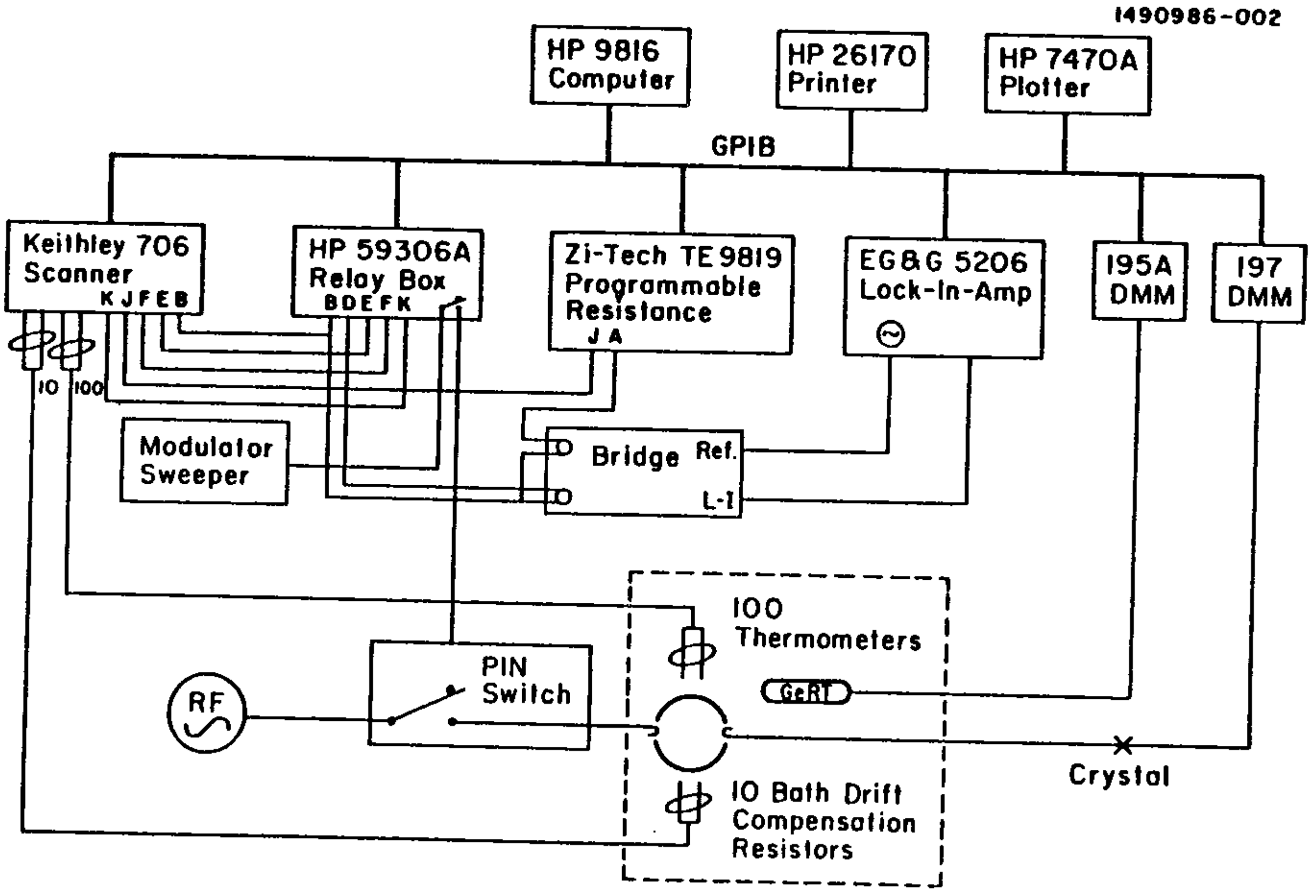

Figure 6: Block diagram of automated data acquisition system for high sensitivity superfluid thermometry on a TE_{011} cavity.

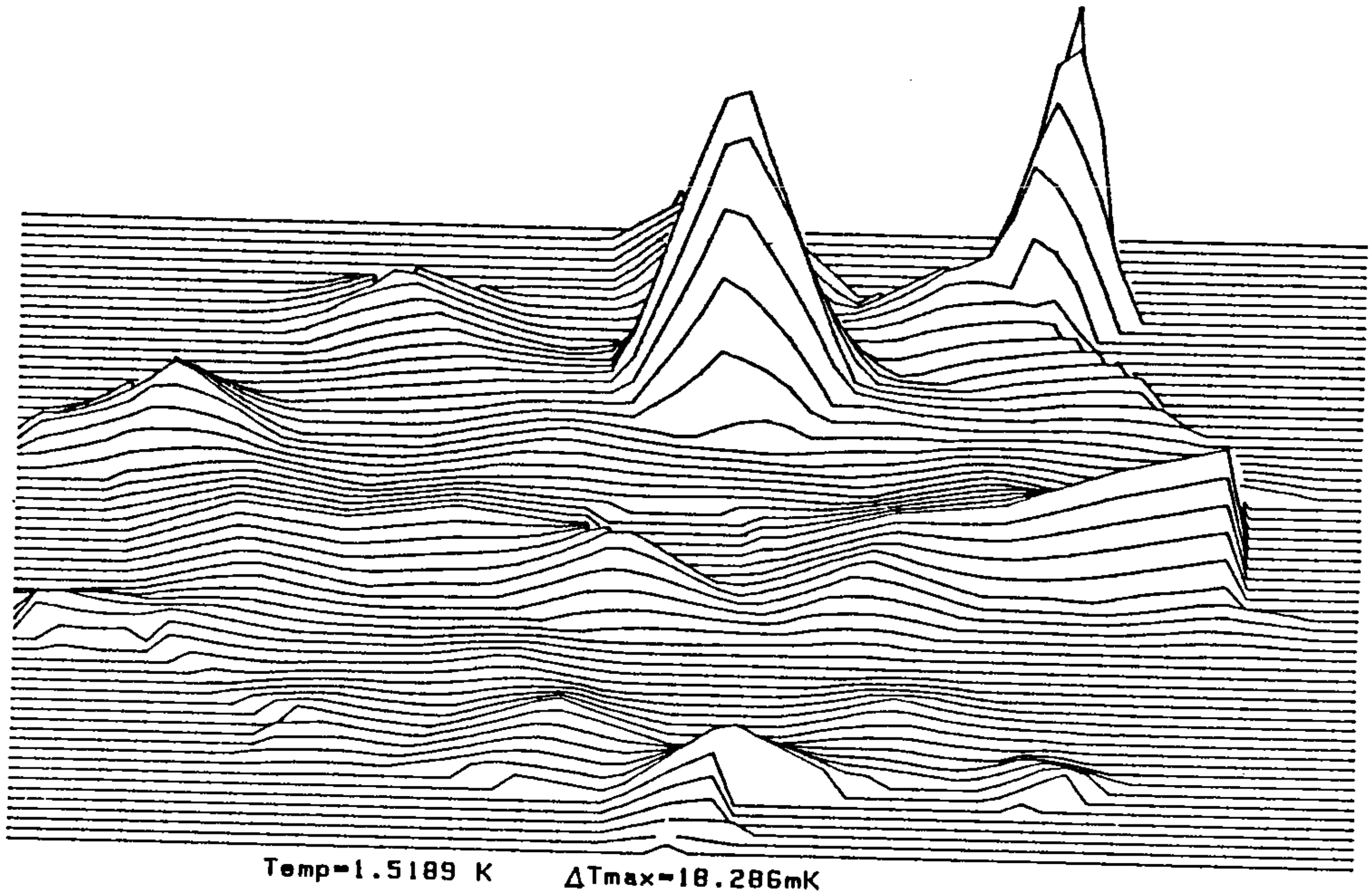

Figure 7: Temperature map of the endplate of the TE_{011} cavity.

One of the enhanced loss regions shows all the behavior of a point like heat source dissipating 1mW of RF power at a magnetic field amplitude of ~100 Oe. The average surface resistance of the area sampled by the sensing thermometer is estimated to be 50 nOhm. It is very interesting to note that this region is surrounded by areas with much lower losses and that this is observable in a cavity with Q_0~$3x10^7$ due to poor flange connections.

Application of this technique at much higher field levels should permit the detection of even lower surface resistances, corresponding to Q-values well above 10^{11}. In addition, the use of a demountable endplate is of great value for systematic studies of loss mechanisms, the reliability of various surface treatments, and the investigation of other superconducting materials.

Simplified Quench Locator System

Measurements at DESY on strongly overcoupled 1 GHz cavities driven by a klystron have indicated a breakdown propagation rate of ~100msec/meter. By observing the response sequence of a relatively small number of sensors, one may take advantage of this known propagation rate and reconstruct the quench location. Such a thermometry system has been developed and will be incorporated into each cryostat for HERA. A permanent array of 60 thermometers of the standard Allen-Bradley 100 ohm resistor variety is strapped around each 4-cell cavity and sealed inside the helium vessel. The thermometry system has demonstrated 1mK sensitivity at 4.2 K. Because the cavities are operated at 4.2 K, the thermometer leads may be brought out through a standard room temperature feedthrough near the helium safety burst disk.

During testing the 60 thermometers, each of which has its own warm preamplifier and comparator, are scanned continuously and data is written onto ring memory. Any one of the comparators may serve as the breakdown trigger. After a trigger is received, one complete write is made to the ring memory, creating a 500 msec record of the propagation of the breakdown.

This technique has been demonstrated so far in two applications.[12] The first is on a 4-cell HERA cavity. After this cavity had been tested to 6.5MV/m with no quench, it was contaminated during some reassembly of attachments. Upon retesting, the cavity was breaking down at 3.5MV/m. The integrally mounted sensors were employed, and the quench location identified as near the gravitational low point of the cell nearest the fundamental power coupler (Cell 1). Additional hot spots were located in Cells 2 and 4. Subsequent visual inspection revealed ½ mm stones at the quench and hot spot locations.

A similar system has also been applied to a single cell Nb-Cu explosion bonded cavity with pipe cooling. The thermometers found the quench location to be in the iris region. Upon inspection, it was found that breakdown was caused by poor heat conduction due to a separation of the Nb and Cu at the iris.

Diagnostic Techniques for the Study of Field Emission

As the use of material of higher thermal conductivity has begun to raise the field level at which quench is commonly encountered in superconducting cavities, nonresonant electron loading has become the dominant limitation on cavity field performance. Direct evidence for localized field emission in RF cavities has emerged from temperature maps obtained in subcooled helium.[13] Until recently, however, only a few isolated emitters had been studied. The difficulty lay in the time required for a temperature map using a rotating thermometry system (typically one hour) and the inability mentioned earlier to obtain maps at high RF power levels in subcooled helium.

To improve the understanding of the behavior of RF field emission from cold surfaces, additional data is needed concerning the density of emitters, time dependence of the emission, processing characteristics, and Fowler-Nordheim (F-N) characteristics. In addition, the influence of various cavity treatments on the field emission behavior is an important topic for investigation.

One technique which has found recent application at the University of Wuppertal is a systematic measurement of the X-ray intensity around superconducting cavities with high-sensitivity photodiodes.[14] The radiation produced by impacting electrons is mapped with a rotating frame of eight detectors. Figure 8 shows the resulting peaks at different angles which can provide useful information about the number and F-N field enhancement factor, β, of emitting sites and the changes that occur during processing.

High Speed Thermometry

A high speed thermometry system useful in superfluid helium has been developed at Cornell University[15]. This system consists of 684 stationary but removable thermometers pressed against the outer wall of a single cell 1500 MHz cavity. The thermometer construction is shown schematially in Figure 9. Carbon resistors are imbedded in a G-10 epoxy housing and sealed with Stycast epoxy. The surface of the assembly is ground until the carbon element is exposed and then electrically insulated by several layers of GE-varnish. These thermometers are spring mounted onto printed circuit boards which are contoured to follow the cavity shape. Apiezon N grease is used as thermal bonding agent between each thermometer and the cavity. The 36 boards are arranged at 10° increments around the cavity. The existing temperature mapping electronics with room temperature multiplexers and matrix wiring scheme used for 5-cell cavity testing was expanded to cover the increased number of resistors.

To acquire a temperature map the resistors are scanned twice, once with RF off then with RF on. The entire data acqusition process is complete within 15 seconds. A typical map showing heating due to field emission and a defect is given in Figure 10. Maps can be taken in rapid succession at increasing field levels, so that field dependent

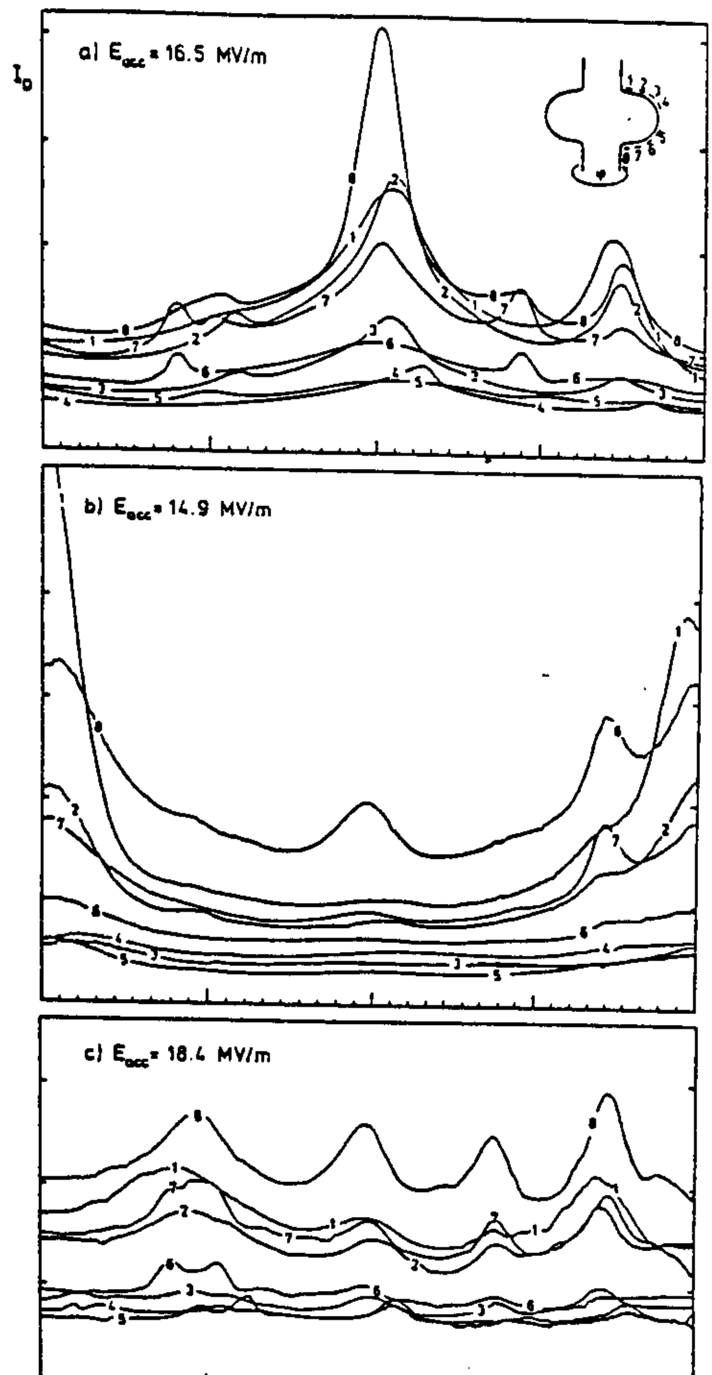

Figure 8: Spatially resolved electron loading with a rotating frame of 8 radiation detectors, a) shortly after initial onset and, status after b) RF processing and, c) He-ion processing.

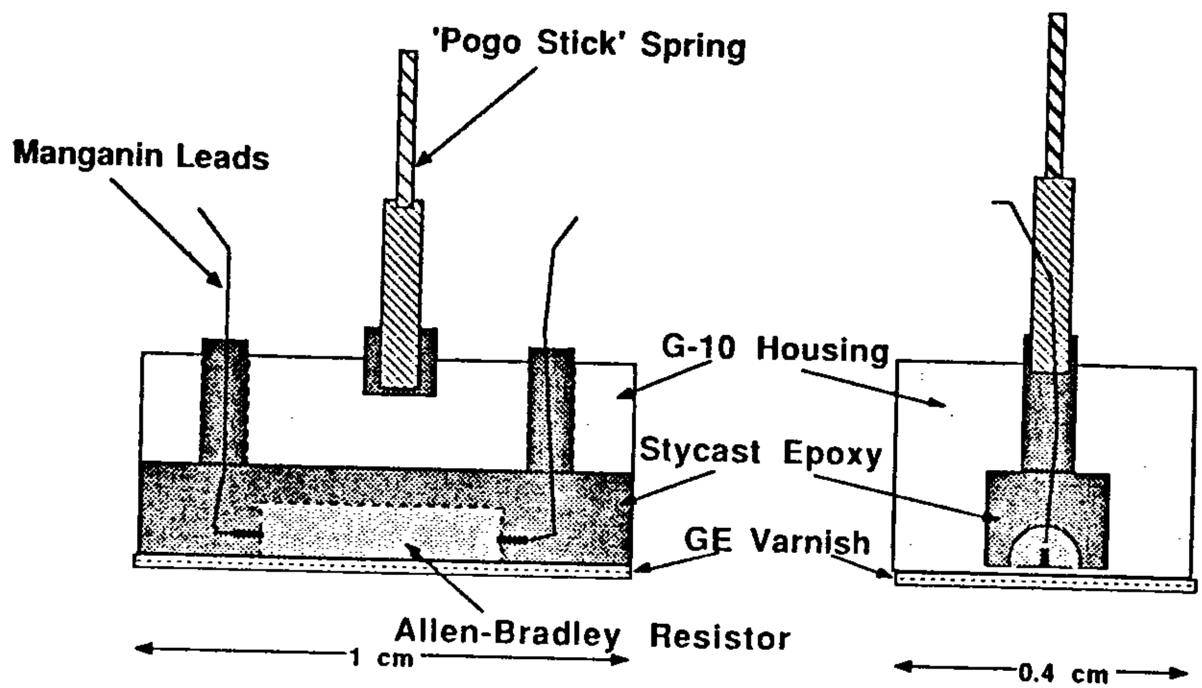

Figure 9: Schematic diagram of thermometer used in the high-speed system.

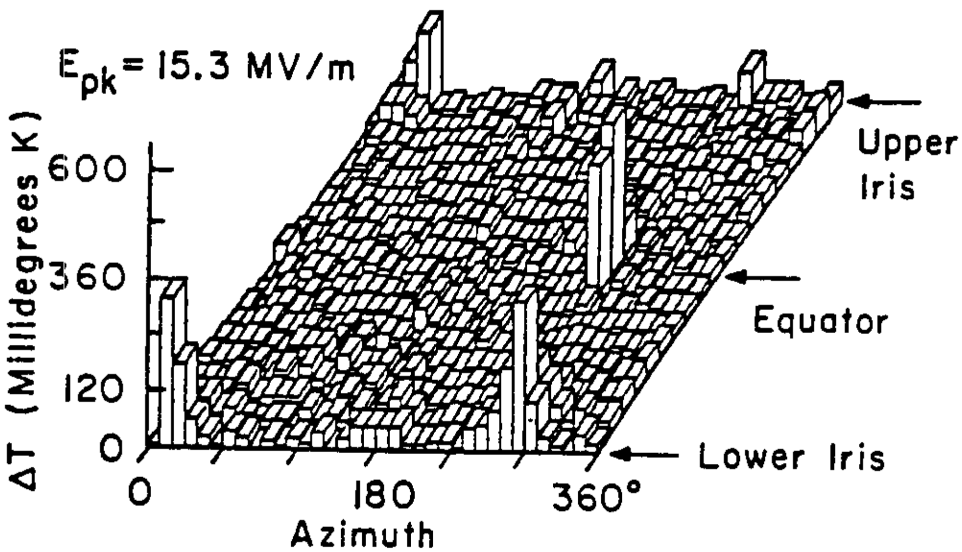

Figure 10: Temperature map of 1500 MHz cavity at 1.5 K. Field emission heating is visible in the iris regions, and weld region defect appears at 270°.

phenomena can be studied. Figure 11 shows longitudinal temperature profiles along fixed meridians at several field levels. One meridian contains a field emitter while another contains a weak superconducting defect in the equator weld region.

A benefit of the high speed mapping is the opportunity to study the time dependent behavior of individual emitter heating. Emitters have often been observed to exhibit switching on a time scale which has previously been inaccesible to thermometric studies (<1 second). The controls for this thermometry system now permit rapid repeated scanning of an individual cavity meridian. Figure 12 shows a scan at 30 msec intervals of the heating profile of one board of resistors. Transient response is clearly demonstrated. These tools offer great promise in the study of field emission in superconducting cavities.

Scanning Laser Acoustic Microscopy

Complete resonating structures, especially those destined for use in accelerators, represent significant investments even before their first cryogenic test. There is strong motivation, then, to apply quality control and diagnostic techniques at as early a stage as is possible. It is standard practice to inspect pre-machining stock for gross surface defects such as oxidizable iron and to visually check surface uniformity by anodization. A technique which has only recently been developed for application to screening of niobium material is Scanning Laser Acoustic Microscopy (SLAM).[16] A rastered laser beam is used to sense the ultrasonic transmission characteristics of the sample under test. The scanning laser beam is employed as a point ultrasonic wave detector.

SLAM may prove very useful since it can rapidly scan large areas, and it can detect interior and surface structural defects and variations in material properties larger than 50 microns. Scan rates of 30 cm^2/sec are possible. SONOSCAN Inc. of Bensenville, IL has been developing this procedure and has examined more than 30 ~100 in^2 niobium plates of $^1/_8$" and $^1/_{16}$" thickness. Identifying characteristics of the acoustic image of various types of flaws have been found. Acoustic attenuation has been found to be dependent on interstitial gas content and the degree of spatial variation of the attenuation on crystal grain size. Internal delaminations are readily identified by the resulting lack of ultrasonic transmission, and localized inclusions and voids larger than about 50 microns are detectable.

In addition, a new class of potential defects has been suggested by SLAM studies. These are near surface rolling delaminations. Some studies on high RRR material, which has much lower strength than standard commercial grade and behaves very doughy during rolling, show such defects.

An automated procedure has been developed which permits scanning and data acquisition for a 9.25"x 9.25" plate in approximately 3 hours. Image recognition software running on a PC requires 12-15 hours for complete analysis.[17]

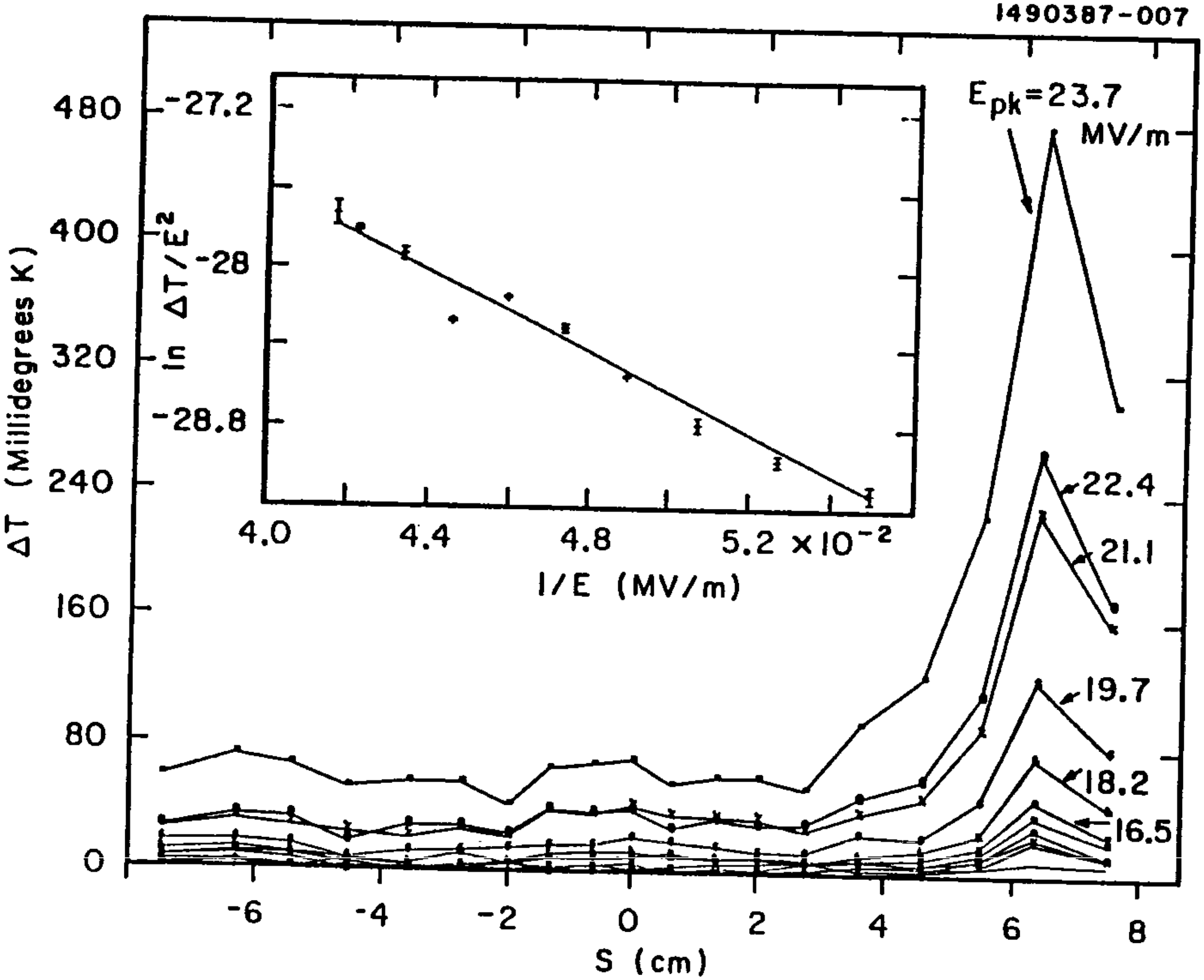

Figure 11: Temperature map due to field emission heating from one emitter at several field levels. The inset show the peak temperature data in a F-N plot.

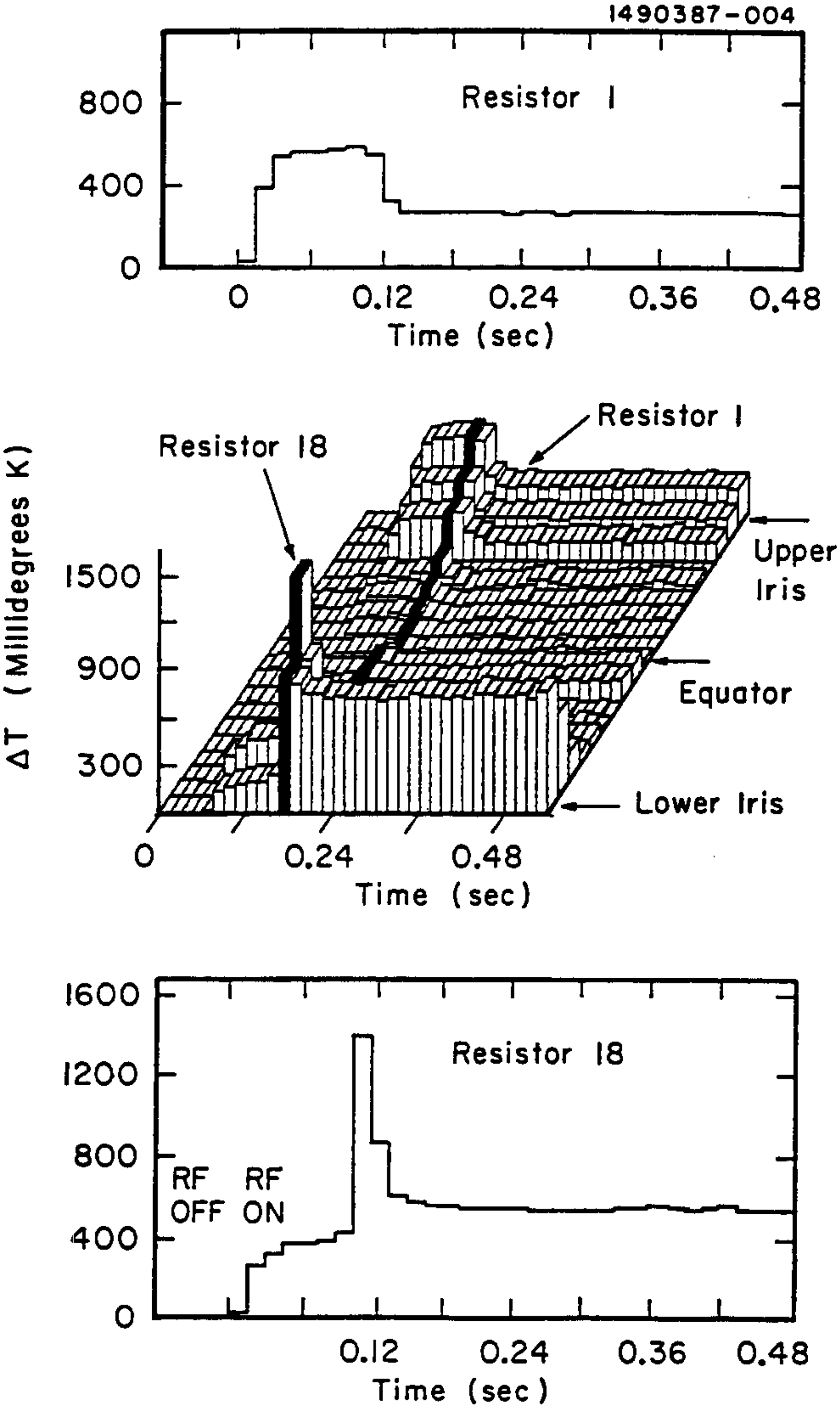

Figure 12: Time dependent temperature map showing switching behavior of emitter on the lower iris. Emission from the upper iris is reduced when the field level drops due to increased emission from the lower iris.

Inductive H_{C2} Measurements

A technique recently developed at CERN employs an inductive measurement of the upper critical field H_{C2} of sheet material.[18] Small samples of area ~3 cm^2 are located between two superconducting coils parallel to an applied d.c. magnetic field which may be varied from 0 to 2 T. Determination of mean RRR values for samples may be made both from the H_{c2} measurements and from the eddy currents induced in the normal conducting state. The appearance, independent of purity level, of much sharper transitions after heat treatments at 1300°C is attributed to increased homogeneity of the residual oxygen content. Such such a correlation may affect the performance of superconducting cavities at high field levels. The technique is equally applicable as a quality control tool in the development of improved fabrication techniques for high T_c layers on superconducting cavities.

Conclusion

While sizable efforts are now being directed toward large scale applications of RF superconductivity, as has been the case for the past 30 years, the full promise is yet to be realized. Material screening techniques should aid in achieving improved reliability, and sensitive cavity thermometry useful below T_λ opens new opportunities for investigation into the behavior of superconducting materials. Perhaps the employment of these new tools will aid in understanding and surmounting the present performance limitations of superconducting cavities.

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